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# Development of a biogenic volatile organic compounds emission inventory for the SCOS97-NARSTO domain

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## Abstract

The Biogenic Emission Inventory Geographic Information System (BEIGIS) is a spatially and temporally resolved biogenic hydrocarbon emissions inventory model developed by the California Air Resources Board that uses California land use/land cover, leaf mass, and emission rate databases within a GIS. BEIGIS simulates hourly emissions of isoprene, monoterpenes, and 2-methyl-3-buten-2-ol (MBO, methylbutenol) at a 1 km<sup>2</sup> resolution. When applied to the Southern California Ozone Study (SCOS97-NARSTO) domain for the 3–7 August 1997 ozone episode, the BEIGIS model predicts total biogenic volatile organic compound (BVOC) emissions of 866 tons for the warmest day (5 August). Depending on whether wildfire emissions are included in the total volatile organic compound (VOC) emissions estimate, modeled BVOC emissions comprise between 16% and 28% of the total VOC inventory. As anthropogenic VOC emissions decline in future years due to control programs, the relative significance of BVOC emissions in the development of ozone control strategies for southern California may assume greater importance.

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**Keywords:** Biogenic hydrocarbons; Isoprene; Monoterpenes; Methylbutenol

## 1. Introduction

Despite significant increases in population growth and vehicle miles traveled, decades of state and local air pollution control programs have improved ozone air quality in southern California. Maximum ozone concentrations have decreased by approximately two-thirds from 1960s-era levels of 0.60 ppm (CARB, 2001). In the South Coast Air Basin (SoCAB), the number of days violating the 1-h National Ambient Air Quality Standard (NAAQS) for ozone (0.12 ppm) have declined from an average 165 days during the decade 1980–1989, to 99 days during 1990–1999. However, for southern California to attain the ozone NAAQS by the federally mandated date of 2010, additional reactive organic gas (volatile organic compound, VOC) and NO<sub>x</sub> control measures will be necessary.

Biogenic VOCs (BVOCs) may have significant impacts on regional air quality due to the magnitude of their emissions as well as their photochemical reactivity (Winer et al., 1983; Chameides et al., 1988; Lamb et al., 1993; Geron et al., 1995; Guenther et al., 2000). For example, the most common BVOC, isoprene, is approximately 3 times more photochemically reactive than a weighted average of VOCs emitted in vehicle exhaust (Carter, 1994). Depending upon the estimated contribution of BVOCs to southern California's VOC emission inventory and ozone air quality, future ozone control strategies for the region may therefore reflect differential emphases for control of anthropogenic VOC versus NO<sub>x</sub> emissions. To help provide a technically sound basis for developing appropriate control strategies, a multiagency taskforce undertook the 1997 Southern California Ozone Study (SCOS97-NARSTO). Primary goals of the SCOS97-NARSTO were to update and improve existing aerometric and emission inventory databases, as well as computer models for representing

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ozone episodes in southern California. These efforts included development by the California Air Resources Board (CARB) of the Biogenic Emission Inventory Geographic Information System (BEIGIS), a California-specific biogenic emission inventory model.

Development of BEIGIS has been motivated by a need to account for the state's pronounced plant species diversity and landscape heterogeneity. There are approximately 6000 native plant species in California (25% of the flora of the continental US) distributed over terrain ranging from basins below sea-level to mountain ranges over 3000 m in elevation (Hickman, 1993). Plant canopies range from scattered and open canopy structures typical of scrublands and savannas, to more closed canopies typical of coniferous forests. Terrain gradients and proximity to marine influence also give rise to more than a dozen climate zones in the state (CEC, 1992). These considerations have prompted the CARB to develop BVOC emission inventory models specific to California.

The development of a BVOC emission inventory for the SCOS97-NARSTO domain was aided by a body of prior biogenic emissions research which had focused on the SoCAB, an area composed of Orange County and the non-desert portions of Los Angeles, Riverside and San Bernardino Counties, comprising the bulk of the South Coast Air Quality Management District (SCAQMD) and approximately 13% of the present SCOS97-NARSTO domain (Winer et al., 1983; Miller and Winer, 1984; Brown and Winer, 1986; Causley and Wilson, 1991; Horie et al., 1991; SCAQMP, 1991, 1994; Corchnoy et al., 1992; Arey et al., 1995; Benjamin et al., 1996, 1997). In the present project, legacy databases were integrated with newer, remotely sensed and GIS-based land use/land cover databases and with day-specific hourly meteorological fields generated by the CALMET model (US EPA, 1995) for the SCOS97-NARSTO domain. Emission algorithms for isoprene, monoterpenes, and 2-methyl-3-buten-2-ol (methylbutenol, MBO) (Guenther et al., 1993; Harley et al., 1998) were also implemented within the GIS scripting environment. The resulting BEIGIS is used to generate day-specific hourly BVOC emissions at 1 km<sup>2</sup> resolution for integration with air quality models.

## 2. BEIGIS inputs

### 2.1. Land use/land cover maps

The initial set of inputs to BEIGIS are GIS-based maps of land use and land cover types. A composite land use and land cover GIS map for the SCOS97-NARSTO domain was compiled from several sources in order to provide sufficient spatial resolution and accuracy to

reflect the heterogeneity of vegetation species in the study area.

A biodiversity database and mapping effort undertaken by the US Geological Survey–Biological Resources Division, called the Gap Analysis Project (GAP), was selected to represent natural areas in the California and Nevada portions of the SCOS97-NARSTO domain (Scott et al., 1993; Davis et al., 1995; Chung and Winer, 1999). The California GAP database was generated from summer 1990 Landsat Thematic Mapper satellite images, 1990 high altitude color infrared imagery, vegetation maps based on historical field surveys, and other miscellaneous vegetation maps and ground surveys. California's GAP coverage is comprised of approximately 21,000 polygons, aggregated into 272 natural community types. The GAP minimum mapping unit is 100 ha (1 km<sup>2</sup>). Each GAP polygon is comprised of up to three vegetation assemblages (a primary, secondary, and for some polygons, a tertiary assemblage), with each assemblage occupying a fraction of the polygon area. In addition, each assemblage is comprised of up to three co-dominant species, each species contributing  $\geq 20\%$  of the assemblage's relative cover. Species canopy cover within individual polygons was estimated as  $FC \times CW$ , where the parameter FC is the fractional canopy cover defined as the fractional area (ranging between 0 and 1) of the polygon occupied by an assemblage, and CW is the co-dominant species weighting factor, such that  $CW = 0.33, 0.50$ , or  $1.0$  for assemblages comprised of 3, 2, or 1 species, respectively. For example, a hypothetical 100 km<sup>2</sup> polygon is comprised of primary and secondary assemblages occupying 65% and 35% of the polygon area, respectively. If the primary assemblage is comprised of two species A and B, the co-species weighting factor for each is 0.5 and the canopy cover for each species is  $(0.65 \times 0.5 \times 100 \text{ km}^2)$ . If the secondary assemblage is comprised of species B, C and D, the canopy cover for each species is  $(0.35 \times 0.33 \times 100 \text{ km}^2)$ . The total canopy cover for species B within the polygon is then  $[(0.65 \times 0.5) + (0.35 \times 0.33)] \times 100 \text{ km}^2$  or 44 km<sup>2</sup>. The estimated canopy cover of a given species in a polygon therefore reflects the weighted contributions from all assemblages in that polygon.

A GIS map and data set similar to GAP (i.e. vegetation types in the coverage are based upon a modified Holland classification system) for portions of northern Mexico were also integrated into the SCOS97-NARSTO model domain (Alberto Mendoza, Georgia Institute of Technology, 1999, pers. comm.). The northern Mexico, California and Nevada GAP datasets were combined in order to create a GIS layer representing natural areas in the SCOS97-NARSTO domain. The combined layer represents an area of approximately 154,300 km<sup>2</sup>, of which approximately 47,250 km<sup>2</sup> (30.6%) is comprised of desert or barren areas

distributed in the northeast portion of the SCOS97-NARSTO domain (San Bernardino County and eastern Riverside County), for which the GAP database does not list plant species.

Another 11,550 km<sup>2</sup> (7.5%) of the domain is comprised of agricultural land uses, which also do not list plant species. The majority of agricultural land uses are located in Kern and Riverside counties and the Imperial Valley portions of Imperial County and northern Mexico. Agricultural land uses also exist in small portions of other counties. For agricultural areas in Kern County, a GIS-based crop map was obtained from the county agricultural commission. For other agricultural areas of the SCOS97-NARSTO domain for which crop GIS layers were not available, agricultural land uses represented by the GAP database was used. Lastly, the composite natural areas GIS layer contains rural towns comprising approximately 350 km<sup>2</sup> (0.2%) which also do not list plant species. The residual 95,150 km<sup>2</sup> comprises non-desert vegetated natural areas. For these areas, the GAP database lists approximately 229 plant species, which appear in various combinations as primary, secondary and sometimes tertiary, assemblages within individual polygons.

For urban areas within the SCOS97-NARSTO domain, urban land use GIS maps were obtained from two regional planning agencies: the Southern California Association of Governments (SCAG) and the San Diego Association of Governments (SANDAG).

## 2.2. Emission factors, leaf mass and landscape-scale emission rates

For natural areas, GAP plant species were assigned isoprene and monoterpene emission factors (EFs) ( $\mu\text{g g}^{-1}$  [dry leaf weight]  $\text{h}^{-1}$ ) from Benjamin et al. (1996) and specific leaf weight factors (SLW,  $\text{g}$  [dry leaf weight]  $\text{m}^{-2}$  leaf area) from a database compiled by Nowak and co-workers (2000). Until relatively recently, EF data collected in California have been based on branch enclosure rather than leaf cuvette measurement methods. Leaf cuvette-based isoprene EFs have been found to be 1.75–5 times greater than branch enclosure derived EFs (Guenther et al., 1994, 1996a; Harley et al., 1998; Geron et al., 2001), ascribed in part to self-shading by leaves within enclosed branches. Since the majority of published EF measurements in California were developed using branch enclosure methods, the BEIGIS model used branch enclosure derived EFs for isoprene and monoterpenes. Branch enclosure derived EFs for methylbutenol were unavailable, therefore leaf-cuvette derived methylbutenol EFs from Harley et al. (1998) were used for the MBO emitting conifer species. Within-canopy vertical variation in leaf mass, temperature and solar radiation were not explicitly accounted for in this modeling. Landscape-scale natural area emission rates

at reference conditions (30°C and 1000  $\mu\text{mol m}^{-2} \text{s}^{-1}$  photosynthetically active radiation or PAR) for isoprene, monoterpenes and MBO ( $\text{mg m}^{-2} \text{land h}^{-1}$ ) were derived by mapping GAP species FC, CW factor, SLW factors, and EFs, to 1 km<sup>2</sup> grids and multiplying by a remotely sensed 1 km<sup>2</sup> resolution leaf area index (LAI,  $\text{m}^2 \text{leaf m}^{-2} \text{land}$ ) GIS layer from Nikolov (1999).

Landscape-scale urban land use isoprene and monoterpene emission rates ( $\text{mg m}^{-2} \text{land h}^{-1}$ ) at reference conditions from Benjamin et al. (1997) were assigned to urban land use polygons in the SCAG/SANDAG layer and gridded to a 1 km<sup>2</sup> resolution. Urban land use emission rates represent aggregations of plant species for urban land use types as described by Horie et al. (1991) and EFs as developed by Benjamin et al. (1996).

For the Kern County agricultural area, landscape-scale monoterpene emission rates at reference conditions were derived by assigning to the crop GIS layer monoterpene EFs reported by Winer et al. (1992) normalized to 30°C using the monoterpene emission algorithm of Guenther et al. (1993) and an assumed SLW factor of 100 g [dry leaf weight]  $\text{m}^{-2}$  leaf. Crop SLW and EFs were then gridded to 1 km<sup>2</sup> resolution and multiplied by the remotely sensed LAI layer. For other agricultural areas represented by the GAP database but for which crop GIS layers were unavailable, a default crop monoterpene EF of 3  $\mu\text{g g}^{-1}$  [dry leaf weight]  $\text{h}^{-1}$  was used. The default crop monoterpene EF was derived from a generic monoterpene emission rate for agricultural land use reported by Benjamin et al. (1997) (0.3  $\text{mg m}^{-2} \text{land h}^{-1}$ ), an SLW factor of 100 g [dry leaf weight]  $\text{m}^{-2}$  leaf, and an LAI value of 1  $\text{m}^2 \text{leaf m}^{-2} \text{land}$ .

In addition to isoprene, monoterpenes, and MBO, other organic compounds are emitted by vegetation. Guenther et al. (1994) estimate that the other VOCs (OVOCs) comprise 8–73% of total BVOCs. BEIGIS however does not explicitly account for OVOCs at this time, because little data exist from which to construct OVOC EFs or emission algorithms for California vegetation. An adjustment factor of 30% is applied to the total isoprene, monoterpene and MBO inventory to account for the OVOC fraction, to which is applied a chemical speciation profile from Lamanna and Goldstein, 1999) (Paul Allen, pers. comm.; CARB, 2001). The OVOC chemical speciation profile is based upon above-canopy ambient air BVOC measurements at Blodgett Experimental Forest, a 1315 m elevation Ponderosa Pine plantation in the central Sierra Nevada of California. The assumed OVOC profile therefore may have limited applicability to natural areas of the SCOS97-NARSTO domain, which, in addition to conifer forests, are comprised of savannas, chaparral and scrublands.

Landscape-scale 1 km<sup>2</sup> resolution emission rate layers for natural, urban, and agricultural areas were then aggregated to construct single layers of gridded

isoprene, monoterpene, and methylbutenol emission rates at reference conditions for the SCOS97-NARSTO domain.

### 2.3. Application of environmental correction algorithms

In the BEIGIS model, the effects of spatial variation in ambient air temperature and light intensity on BVOC emissions are taken into account. Isoprene, monoterpene, and MBO emission rate grid layers were environmentally adjusted using emission algorithms (Guenther et al., 1993; Harley et al., 1998) driven by hourly gridded air temperature and solar radiation fields. Hourly temperature fields gridded at  $5 \times 5 \text{ km}^2$  resolution for the SCOS97-NARSTO domain were generated using the CALMET model (US EPA, 1995) from meteorological data. Since SCOS97-NARSTO model episodes were relatively cloud-free and hourly surface station solar radiation data exhibited little spatial variation across the domain, uniform PAR fields for each hour of the day were assumed. PAR was calculated as  $0.42 \times \text{SRAD} \times (4.6 \mu\text{mol photons m}^{-2} \text{s}^{-1})$

$[\text{W m}^{-2}]^{-1}$ , where SRAD is full sun (direct + diffuse) radiation ( $\text{W m}^{-2}$ ) in the visible spectrum.

### 3. Model results

BVOC emissions for the SCOS97-NARSTO ozone episode of 3–7 August 1997 were developed using the BEIGIS model. During this episode the maximum 1-h ozone concentration observed in the SoCAB was 19 ppbm, with maxima elsewhere in the SCOS97-NARSTO domain ranging from 9 (northern Mexico) to 14 ppbm (Mojave Desert) (CARB, 2002). Figs. 1–3 illustrate the spatial distributions of modeled isoprene, monoterpene, and MBO emissions in the SCOS97-NARSTO domain for the hour ending at 1300 on the warmest episode day, 5 August 1997.

As shown in Fig. 1, isoprene emissions are spatially distributed in a pattern corresponding to coastal and inland montane natural areas, and urbanized lowlands ( $37,215 \text{ km}^2$ ). Isoprene emission maxima ranging between 6 and  $12 \text{ mg m}^{-2} \text{h}^{-1}$  occur in natural areas

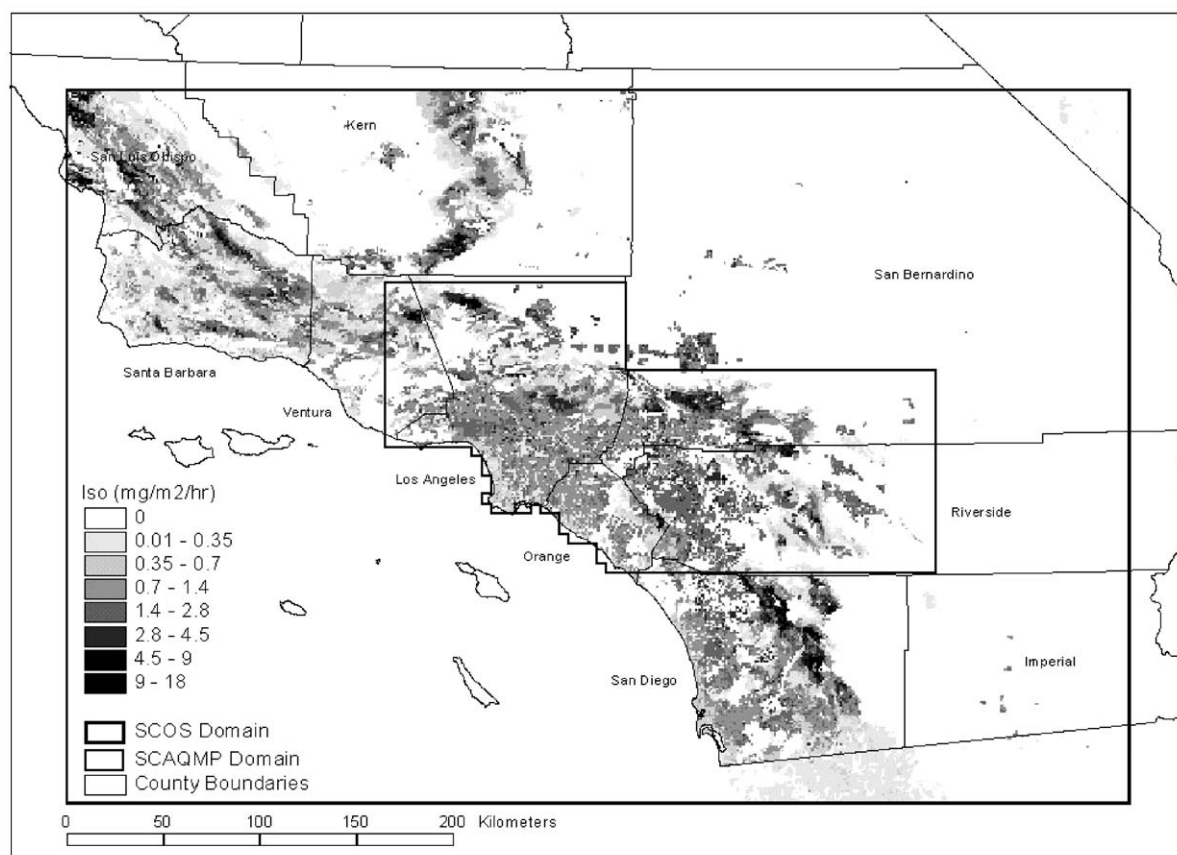


Fig. 1. Isoprene emissions ( $\text{mg m}^{-2} \text{h}^{-1}$ ) for the hour ending at 1300 PST on 5 August 1997.



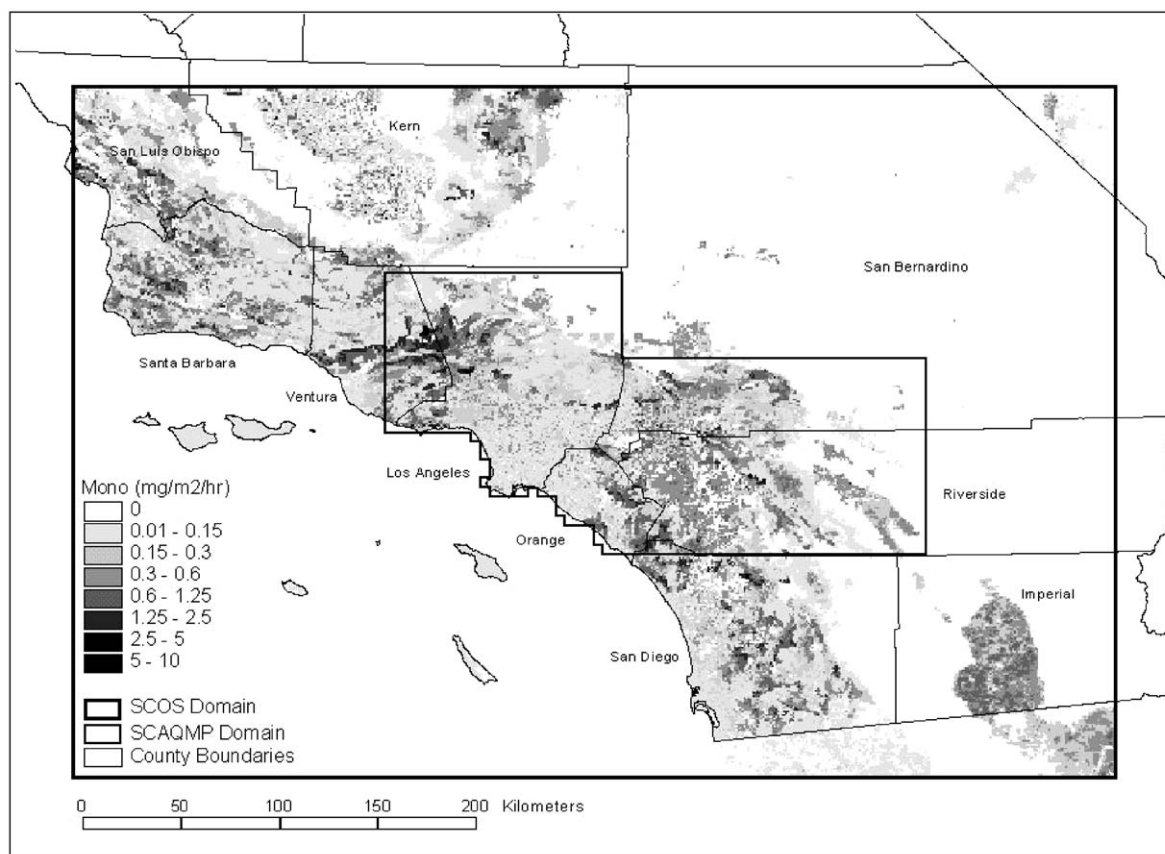


Fig. 2. Monoterpane emissions ( $\text{mg m}^{-2} \text{h}^{-1}$ ) for the hour ending at 1300 PST on 5 August 1997.

dominated by isoprene-emitting native oak species and temperatures ranging from  $28.7^{\circ}\text{C}$  to  $43.1^{\circ}\text{C}$ . Modeled isoprene emission maxima in the SCOS97-NARSTO domain are comparable to above-canopy isoprene flux measurements near Oak Ridge, Tennessee ( $2\text{--}9 \text{ mg m}^{-2} \text{h}^{-1}$ ) (Guenther et al., 1996b). Urban areas in the Los Angeles basin exhibit isoprene emissions of about  $1 \text{ mg m}^{-2} \text{h}^{-1}$ , with isolated cells showing slightly elevated emissions ranging between 3 and  $4 \text{ mg m}^{-2} \text{h}^{-1}$ . Isoprene emissions in urban areas reflect contributions from introduced vegetation, such as eucalyptus species.

Monoterpane emissions have a similar spatial distribution as the emissions of isoprene, but over a larger geographic area ( $56,118 \text{ km}^2$ ) (Fig. 2). Inland desert areas contain sparse natural vegetation and exhibit little or no emissions. Monoterpane emission maxima ranging between 4 and  $5 \text{ mg m}^{-2} \text{h}^{-1}$  are distributed throughout natural areas associated with sagebrush (*Artemisia* spp.) and sage (*Salvia* spp.), species which were assigned monoterpane EFs of 12 and  $8 \mu\text{g g}^{-1}$  [dry leaf weight]  $\text{h}^{-1}$ , respectively. Temperatures ranged between  $29.3$  and  $40.3^{\circ}\text{C}$  for grid cells with monoterpane emissions greater than  $4 \text{ mg m}^{-2} \text{h}^{-1}$ . Modeled monoterpane

emission maxima in the SCOS97-NARSTO domain are a factor of 5–10 times greater than emissions reported from forest measurements in Georgia and Alabama ( $0.6\text{--}0.8 \text{ mg m}^{-2} \text{h}^{-1}$ ) (Guenther et al., 1996a) and in the central Sierra Nevada ( $0.5\text{--}0.9 \text{ mg m}^{-2} \text{h}^{-1}$ ) (Schade et al., 1999). Chamise-Redshank Chaparral and Coastal Scrub communities (also associated with *Artemisia* and *Salvia*) exhibit emissions in the range of  $1\text{--}2 \text{ mg m}^{-2} \text{h}^{-1}$ , a factor 2 greater than the above reported emissions. Crop monoterpane emissions averaging between 0.1 and  $0.2 \text{ mg m}^{-2} \text{h}^{-1}$  are distributed in Kern County and the intensively farmed Imperial Valley. In both of these agricultural areas, modeled monoterpane emission maxima range between 1 and  $2 \text{ mg m}^{-2} \text{h}^{-1}$ . Several  $1 \text{ km}^2$  cells associated with tomato cultivation (EFs of 20 and  $32 \mu\text{g g}^{-1}$  [dry leaf weight]  $\text{h}^{-1}$  for table and processing varieties, respectively) and with temperatures above  $39^{\circ}\text{C}$ , exhibit emissions greater than  $4 \text{ mg m}^{-2} \text{h}^{-1}$ . Urban vegetation monoterpane emissions range between 0.1 and  $0.2 \text{ mg m}^{-2} \text{h}^{-1}$ .

Methylbutenol emissions have been reported for only a few conifer species, such as Coulter, Foothill, Jeffrey, Ponderosa, and Lodgepole pine. MBO emissions (Fig. 3)

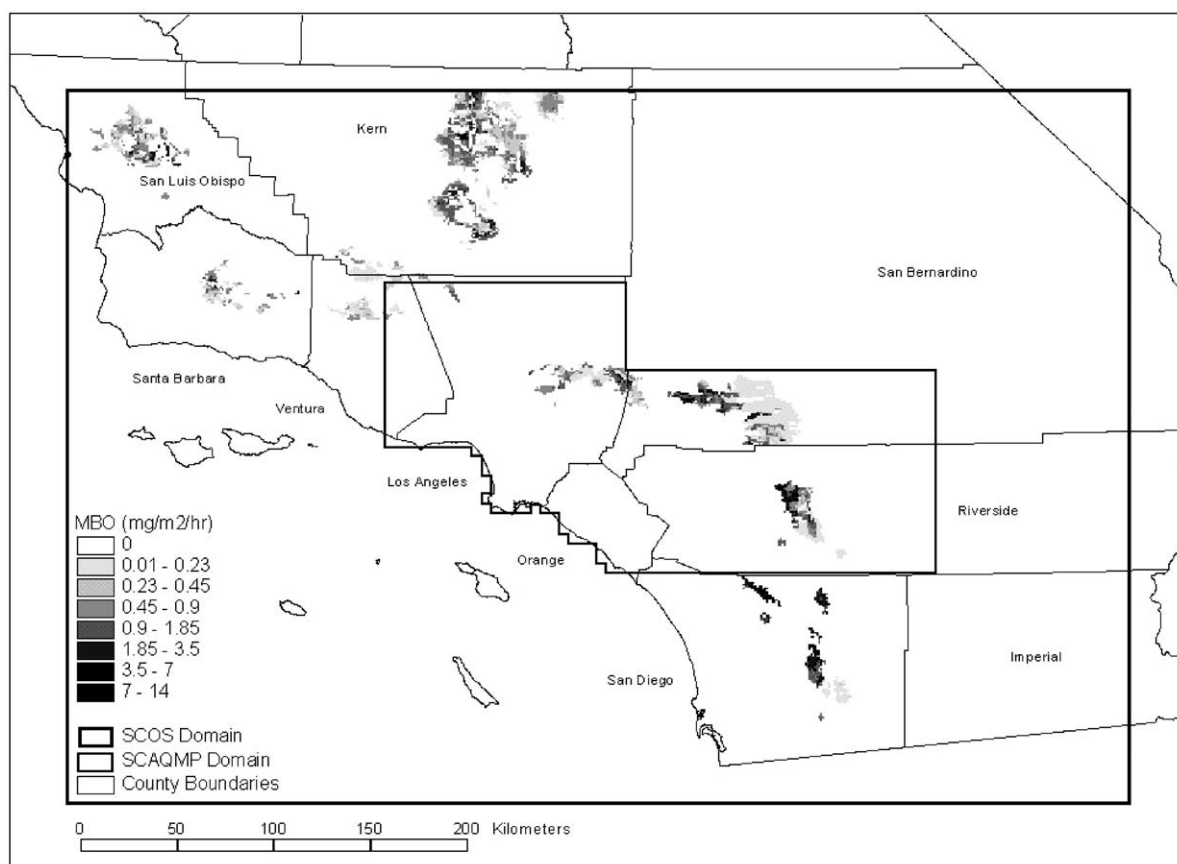


Fig. 3. MBO emissions ( $\text{mg m}^{-2} \text{h}^{-1}$ ) for the hour ending at 1300 PST on 5 August 1997.

are distributed among a limited number of upper elevation areas in the SCOS97-NARSTO domain, corresponding to geographic ranges for these pine species. Modeled maximum MBO emissions generally range between 1.4 and  $4.3 \text{ mg m}^{-2} \text{h}^{-1}$ , similar to reported MBO emissions measured above a Ponderosa Pine plantation in the central Sierra Nevada mountains of California (Schade et al., 2000). A few grid cells associated with Coulter and Foothill Pine (species assigned EFs of  $101.8$  and  $96.1 \mu\text{g g}^{-1}$  [dry leaf weight]  $\text{h}^{-1}$ , respectively) however exhibit hourly emissions of up to  $18.6 \text{ mg m}^{-2} \text{h}^{-1}$ .

Fig. 4 illustrates the modeled diurnal trend in isoprene, monoterpenes, and MBO emissions for the 3–7 August 1997 time period for the SCOS97-NARSTO domain. The temperature dependence of isoprene, monoterpenes, and MBO emissions is reflected in both their diurnal emissions patterns, as well as in the warming and cooling trend over the 5 day period. The light dependence of isoprene and MBO emissions is reflected in the cessation of emissions of these chemical species during nighttime hours. On the warmest day (5 August), isoprene emissions peak after midday at

approximately 45 tons/h (tph), with monoterpene and MBO emissions at less than 20 and 5 tph, respectively. The significantly higher isoprene emissions relative to monoterpene and MBO reflects the abundance of isoprene-emitting plant species in the SCOS97-NARSTO domain as well as the high emission rates for many isoprene-emitting species. For example, isoprene EFs assigned to native oaks ranged between  $13$  and  $54 \mu\text{g g}^{-1}$  [dry leaf weight]  $\text{h}^{-1}$ . By contrast, monoterpene EFs for conifers and sage range between  $3$  and  $12 \mu\text{g g}^{-1}$  [dry leaf weight]  $\text{h}^{-1}$ .

Modeled BVOC emissions comprise a significant fraction of the total VOC inventory in the SCOS97-NARSTO domain. Depending upon whether wildfire emissions are included in the total VOC emissions estimate, the contribution of BVOCs comprises between 16% and 28% of the overall VOC inventory in the SCOS97-NARSTO domain on 5 August 1997 (Table 1). As shown in Table 1, modeled BVOC emissions on 5 August 1997 totaled approximately 866 tons (including OVOCs), while wildfire, geogenic, and anthropogenic VOC emissions were estimated at 2246, 24, and 2212 tons, respectively (Paul Allen, pers. comm.; CARB,

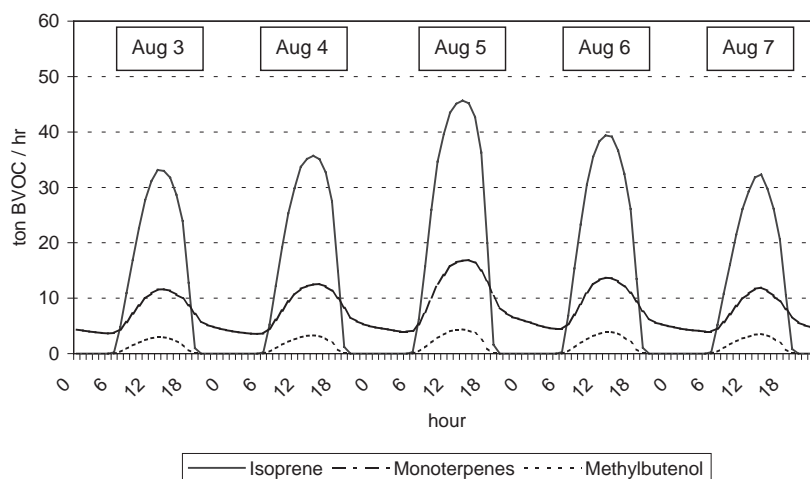


Fig. 4. Diurnal trends in BEIGIS-modeled BVOC emissions for the 3–7 August 1997 ozone episode for the SCOS97-NARSTO domain.

Table 1  
VOC emissions in the SCOS domain on 5 August 1997

	Including Wildfires		Excluding Wildfires	
	Tons per day	Percent of total	Tons per day	Percent of total
BVOC <sup>a</sup>	866	16	866	28
Wildfire VOC	2246	42		
Geogenic VOC <sup>b</sup>	24	<1	24	1
Anthropogenic VOC	2212	41	2212	71
Total	5348	100	3102	100

<sup>a</sup> BVOC total includes 135 tons OVOCs.

<sup>b</sup> Natural seeps from petroleum deposits.

2001). Wildfire VOC emissions were very significant on this particular ozone episode day, due to some large fires burning at the time.

#### 4. Comparison to prior inventories

Previous BVOC studies in southern California (SCAQMP, 1991, 1994; Benjamin et al., 1997) focused on the SCAQMP modeling domain (Fig. 1), an area significantly smaller than the SCOS97-NARSTO domain. To allow comparison of the present study results with BVOC emission inventories reported in previous studies, only emissions within the SCAQMP boundary were considered. The resulting estimates are compiled in Table 2 and represent BVOC estimates for a common domain, similar land surface inputs, and varying meteorological inputs. The SCAQMP (1991, 1994) BVOC inventories shown in Table 2 are based on modeling for 9 and 15 days, respectively, for the period June 1985–September 1987 and are represented as a range to reflect the variability of emissions over these

Table 2  
Comparison of selected southern California BVOC emission inventories for the SCAQMP modeling domain

Study	Tons per day		
	Isoprene	Monoterpenes	Iso + Mono
SCAQMP (1991)	*	*	150–250
SCAQMP (1994)	*	*	111–275
Benjamin et al. (1997)	94–107	86–92	180–200
This Study	188	94	282

\*Not reported.

episode days. The lower estimates reported in the SCAQMP (1991, 1994) BVOC inventories reflect average summer day, rather than ozone-episode day, temperatures. The upper estimates were based upon higher-than-average temperatures during ozone episode days. The range of BVOC emissions reported by Benjamin et al. (1997) were based on temperatures from 19 highest ozone-episode day temperatures for the

period September 1987–June 1992 and also reflect a range of episode days. The BEIGIS results presented in this paper represent the average of 5 days from a single ozone episode (8 March 1997–8 July 1997).

With respect to summed isoprene and monoterpene emissions, the BEIGIS results are slightly greater than the upper value of the 1991 SCAQMP and in close agreement with the upper value of the 1994 SCAQMP. The summed isoprene and monoterpene result is a factor 1.4–1.5 greater than the Benjamin et al. (1997) result. The BEIGIS isoprene result is approximately 1.8 times greater than the upper estimate from Benjamin et al. (1997). The difference may be due to how natural areas and canopy effects are represented in the two inventories. For natural areas, Benjamin et al. (1997) employed 9 generic natural land use/land cover types, summer leaf biomass factors, and landscape emission rates. Isoprene emission rates at reference conditions for woodland, chaparral, and forest types ranged between 0.6 and 2.7 mg m<sup>-2</sup> h<sup>-1</sup> (Benjamin et al., 1997). In the BEIGIS model, reference isoprene emission rates for natural areas represented by the GAP database within the SCAQMP domain range between 0 and 9.45 mg m<sup>-2</sup> h<sup>-1</sup>. In the work of Benjamin et al. (1997), canopy shade effects were also accounted for by applying a 23% reduction factor to emissions, based on an analysis by the SCAQMD (SCAQMP, 1991).

BEIGIS estimated emissions for 5 August 1997 (497 tons, including OVOCs) represent 22% of the total (2278 tons) and 32% of the anthropogenic (1535 tons) VOC emissions for the SCAQMP modeling domain. By contrast, the BVOC inventory estimated by Benjamin et al. (1997) (Table 2) represents between 8% and 9% of the anthropogenic VOC emissions inventory for the 1987 summer ozone episode (approximately 2000 tons) (SCAQMP, 1996). The increase in the relative contribution of biogenic emissions between this study and Benjamin et al. (1997) reflects several factors, including different vegetation and meteorological inputs, as well as a decline in anthropogenic emissions between 1987 and 1997.

## 5. Model uncertainties

Inputs to BEIGIS, such as emission rates, leaf mass factors, land use/land cover maps, and satellite-derived LAI values have been assessed by a number of researchers (Winer et al., 1998; Chung and Winer, 1999; Karlik and McKay, 1999; Karlik, 2001; Winer and Karlik, 2001).

Isoprene and monoterpene EFs utilized by BEIGIS for plant species in California's urban, agricultural, and natural landscapes are derived from in situ branch enclosure measurements and taxonomic assignments (Benjamin et al., 1996). Although measured emission

rates are used where available, assignment of measured EFs to unmeasured species based upon taxonomic relationship introduces uncertainties. Karlik and Winer (2001) measured isoprene EFs of plant species to test taxonomically assigned EFs of Benjamin et al. (1996). They reported measured branch-level isoprene EFs for 13 of 19 species were within  $\pm 50\%$  of taxonomically predicted EFs. Genus-level assignments were in generally good agreement with measured isoprene rates, with the exception of *Quercus*, where emissions varied widely about the predicted mean of 24.8  $\mu\text{g g}^{-1} \text{h}^{-1}$ , from below detection limit for *Q. suber* to 54  $\mu\text{g g}^{-1} \text{h}^{-1}$  for *Q. kelloggii*. The uncertainty associated with the monoterpene and OVOC emissions estimates have not been quantified. OVOCs are an added fraction to the BEIGIS BVOC inventory to which is applied a chemical speciation profile which may not be representative of natural areas in the SCOS97-NARSTO domain.

As noted previously, systematic differences have been reported in the literature for leaf cuvette versus branch enclosure derived EFs. Geron et al. (2001) assessed taxonomic rate assignments of Benjamin et al. (1996) by measuring leaf cuvette isoprene EFs for a number of eastern US and native California oak species. For *Q. chrysolepis*, *Q. engelmannii*, *Q. kelloggii*, *Q. falcata* and *Populus trichocarpa*, measured leaf cuvette emissions were approximately a factor of 2–5 times greater than the taxonomically predicted branch-level EFs, attributed in part to differences in enclosure type. Guenther et al. (1996a) also observed that isoprene emissions measured via leaf cuvette ranged between 1.5 and 2 times greater than branch-level measurements, due to differences in leaf orientation, self-shading and other factors.

Plant species composition and abundance predicted by the GAP database have been evaluated for several regions of the state. Field data from 8 sites in the SCOS97-NARSTO domain and 6 sites in central California indicate that the GAP database correctly predicted 50–70% of the plant species at the sites surveyed (Winer et al., 1998; Chung and Winer, 1999; Winer and Karlik, 2001). In San Diego County, isoprene and monoterpene emission potentials for 8 polygons estimated according to GAP predicted plant species composition and areal coverage were compared to emission potentials estimated from field sampling (Chung and Winer, 1999). For four of the polygons, emission potentials based on GAP predictions were more than 50% different from emission potentials calculated from field data. When summed over all 8 polygons, the total isoprene emission potential based on field data was 7% greater than the total based upon the GAP prediction. The total monoterpene emission potential for the 8 polygons based on field data was 2% lower than the total based upon the GAP prediction.

Modeled BVOC emissions are also sensitive to uncertainties associated with leaf mass density (LMD)



(g [dry leaf weight]  $\text{m}^{-2}$  land). Although embedded within urban land use BVOC emission rates in Benjamin et al. (1997), leaf mass densities for urban land uses are not explicitly treated in the present model. BEIGIS assumes that reference landscape-scale BVOC emission rates ( $\text{mg m}^{-2}$  land  $\text{h}^{-1}$ ) for urban land uses are spatially unvarying. Thus, the emission rate assigned to a residential land use is the same for a 50-year old neighborhood as it is for a 10- or 20-year old neighborhood. The assumption that LMD and species composition do not vary with urban land use vintage in the SCOS97-NARSTO domain may not be realistic.

For natural areas, LMD is computed from remotely sensed LAI, fractional canopy cover, co-species weighting factors and plant SLW factors. Winer and Karlik (2001) found that ground-surveyed leaf area indices measured in California oak savannas ( $\text{LAI} \sim 1.3$ ) agreed with satellite-derived  $1 \text{ km}^2$  resolution LAI values (between 1 and 2) for those same sites. In the Winer and Karlik (2001) study, a stand of 14 Blue Oak trees (*Q. douglasii*) surrounded by open grassland was measured for crown height, crown radii, and diameter at breast height (DBH). All 14 trees were then harvested, and their stem and leaf areas and (fresh and dried) weights recorded. Mean per-tree LMD was  $730 \text{ g m}^{-2}$ , while site LMD, defined as the total leaf mass of the 14 trees divided by the total study area, was  $310 \text{ g m}^{-2}$ . This site LMD value is in the midrange of LMDs ( $182\text{--}643 \text{ g m}^{-2}$ ) reported by Sidawi and Horie (1992) for oak woodlands in the southern San Joaquin Valley. When the oak leaf mass of the site study area was considered together with surrounding grassland, the LMD decreased by a factor of two. In the BEIGIS model, calculated LMDs for  $1 \text{ km}^2$  grid cells in SCOS97-NARSTO natural areas are often less than  $200 \text{ g m}^{-2}$ . Natural area LMDs utilized by Benjamin et al. (1997) for the SCAQMP domain ranged from 90 (grassland) to 244 (woodland) to  $555 \text{ g m}^{-2}$  (forest). Although further data analyses are needed, these preliminary results support the use of the satellite-derived LAI database as an input to the BEIGIS model.

Potential leaf mass estimation biases from multiplying plant species SLWs by fractional canopy cover areas and co-species weighting factors together with LAI values for  $1 \text{ km}^2$  grid cells are unknown. Computing species leaf mass densities in this manner may over or under-predict a species' contribution to total emissions. The technique may be less problematic for computing leaf masses and emissions of crops, many of which are cultivated in monocultures greater than  $1 \text{ km}^2$ .

## 6. Conclusions

The biogenic volatile organic compound (BVOC) inventory generated using the Biogenic Emission

Inventory Geographic Information System (BEIGIS) model for the SCOS97-NARSTO domain agrees relatively well with three prior southern California BVOC inventories. Field studies indicate that the branch-level emission factors (EFs), GIS vegetation databases and remotely sensed LAI inputs utilized by BEIGIS are reasonable. However, monoterpene and MBO emission maxima predicted by the BEIGIS model are in a few locations higher than measured fluxes reported in the literature. Emission estimate uncertainties arise from unresolved issues concerning the utilization of branch enclosure versus leaf cuvette derived EFs, together with canopy models. Simultaneous BVOC flux measurements at leaf, branch and canopy scales for BVOC significant California landscapes are needed in order to better assess BVOC emission models such as BEIGIS.

Modeled BVOC emissions comprise a significant fraction of the total VOC inventory for the SCOS97-NARSTO domain. On the warmest ozone episode day (5 August 1997), BVOC emissions totaled 866 tons. Depending on whether wildfire emissions are included in the total VOC emissions estimate, modeled BVOC emissions comprise between 16% and 28% of the total VOC inventory. As anthropogenic VOC emissions decline in future years due to control programs, the relative significance of BVOC emissions in the development of ozone control strategies for southern California may assume greater importance.

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